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Effects of dieback on the vegetative, chemical, and physiological status of mangrove forests, Iran

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Abstract: Mangrove forests are valuable resources in tropical and subtropical regions, which have been faced dieback due to various human activities including rapid expansion of shrimp farming, urban development, and pollution, as well as natural factors such as rising sea level, increasing air temperature, drought, and sharp decrease in rainfall. However, the mechanisms of dieback of mangrove forests are not well understood. Therefore, this research aimed to assess the vegetative, chemical, and physiological status of grey mangrove (*Avicennia marina* (Forsk.) Vierh.) forests at different intensities of dieback in the Hormozgan Province, Iran. A total of 40 plots categorized into four dieback intensities (severe, medium, low, and control) were randomly selected for monitoring, and various parameters related to vegetative, chemical, and physiological status of grey mangrove forests were examined. The results revealed that the control group had the highest tree density, seedling density, vitality levels, aerial root density, and aerial root height. Generally, as dieback severity increased, a decrease in demographic and vegetative parameters of trees and seedlings was observed in the dieback treatments. The amounts of heavy metals (lead, cadmium, and nickel) in the sediment, roots, and leaves of grey mangrove trees at different dieback levels indicated that lead levels were the highest in the sediment, roots, and leaves in the severe dieback treatment. At the same time, the control had the lowest values. Cadmium concentrations in the sediment followed the pattern of severe dieback>moderate dieback>low dieback>control with no significant differences in the roots and leaves. Nickel amounts in all three parts, i.e., sediment, roots, and leaves showed the highest levels in the severe dieback treatment. Furthermore, metal level analysis in the organs of grey mangrove trees at different dieback levels revealed that lead and nickel were more abundant in the root organ compared with the leaves. In contrast, the leaf organ exhibited the highest cadmium levels. Dieback significantly impacted water electrical conductivity (EC), soil organic carbon (SOC), and chlorophyll *a*, *b*, and total chlorophyll contents, with the highest values observed in the severe dieback treatment. However, no significant differences were observed in acidity and carotenoid levels. In conclusion, sediment erosion and heavy metal accumulation were critical contributors to dieback of grey mangrove trees, affecting their physiological, vegetative, and plant production characteristics. As the ability of these plants to rehabilitate has diminished, effective management planning is imperative in dieback-affected areas.

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1 Introduction

From an ecological perspective, coastal habitats are among the most critical ecosystems on the Earth. Among these habitats, mangrove forests stand out as one of the world's most vital coastal systems due to their unique value. Mangrove forests are of significance to coastal governments because of the comprehensive ecosystem services they provide (Moslehi, 2018). Over the past decades, these ecosystems have undergone various changes due to human activities (Wang et al., 2021). Climate change, with its various components, including sea level rise, temperature fluctuations, changes in atmospheric carbon dioxide concentration, oceanic cycle patterns, shifts in rainfall patterns, and the increased occurrence of storms, profoundly affects the health of mangrove forests. It is worth noting that these coastal areas face threats such as erosion, flooding, strong waves, and tsunamis. However, among all these factors, the most significant threat to mangrove forests is posed by human intervention, specifically pollution and deforestation (Delfan and Ghodrati-Shojaii, 2021).

Dieback of mangrove forests is one of the most pressing threats observed globally today. Unfortunately, there is limited information available on the dieback of mangrove forests and the global factors influencing them. The following studies shed light on this issue, for example, Ghosh et al. (2021) researched dynamic changes in the mangrove forests and biodiversity using hyperspectral data from 2011 to 2014. They found that in some areas, an increase in saline solutions decreased the proportion of mangrove trees over the years. However, species like *A. marina* and *Avicennia officinalis* Linn, known for their salt tolerance, showed increased presence. Duke et al. (2017) investigated the loss of mangrove forests of the Gulf of Carpentaria in Australia from 2015 to 2016. The cause of this loss was not fully explained, but it is believed to be linked to an extreme weather event characterized by high temperatures and low precipitation with no hurricane-force winds. Nguyen et al. (2021) researched the health of mangrove forests in the Thanh Hoa Province, Vietnam, focusing on fungal pathogens related to plant deterioration. Their results identified four main fungal genera responsible for leaf spots and stem dieback Mafi Gholami et al. (2017) investigated changes of mangrove forests in the Hormozgan Province from 1986 to 2016. They found that environmental factors like climate changes, local geomorphology, hydrology, and human activities limited the development of mangrove forests. Yaqoubzadeh et al. (2020) explored the impact of docks on the vegetative and reproductive characteristics of mangrove trees in Khor-e-Azini Wetland and Khamir Port, Iran. Their results revealed critically high levels of nickel in the sediments of *A. marina* and *Rhizophora mucronata* Poir. Other studies in the Persian Gulf region, such as those by AboHassan (2013), Al Hagibi et al. (2018), Saleh et al. (2018), and Aljahdali and Alhassan (2020), have also reported heavy metal concentrations in sediments ranging from 14 to 98 μg/g for copper, from 44 to 306 μg/g for zinc, and from 8 to 99 μg/g for nickel. These results underscore the need to thoroughly investigate and control heavy metal pollution in the mangrove forests of Iran. Additionally, sediment deposition is crucial in shaping vegetative and physical-chemical characteristics of mangrove trees. Nardin et al. (2021) researched the impact of sediment deposition on mangrove forests in the Mekong Delta, Vietnam. Their findings highlighted that significant deposition could bury mangrove roots and pneumatophores, leading to forest dieback.

Grey mangrove forests near the port, primarily used for refueling barges, are highly susceptible to fuel spills during refueling operations (Dittman et al., 2022). Unfortunately, grey mangrove forests face these pollution problems due to their proximity to pollution sources in the Hormozgan Province, Iran. Consequently, these grey mangrove forests have undergone significant changes in recent years and are experiencing dieback. Given the multiple factors contributing to dieback,

especially their proximity to pollution sources, this study aims to assess the vegetative, chemical, and physiological status of grey mangrove trees in different intensities of dieback.

2 Materials and methods

2.1 Study area

Sirik Port, covering an area of 3500 km², is situated 75 km southeast of Minab on the coast of the Oman Sea (Bijani, 2019). The study area is within the Khor-e-Azini Wetland (26°18′02″–26°26′26″N, 57°03′26″–57°06′31″E), approximately 35 km from the Sirik Port. The study area experiences an average annual rainfall of 204.4 mm, ranging from 30.3 to 399.6 mm (Bijani, 2019; Moslehi et al., 2021). The study area exhibits a dry and desert climate, with water scarcity particularly pronounced in the first 9 months of the year (Kheirandish et al., 2015; Bijani, 2019). Soil texture predominantly consists of silty loam (Moslehi et al., 2021) in the surface soil, while the bottom soil is characterized by loam-clay-sand. Additionally, soil acidity (pH) ranges from 7.77 to 7.96. EC ranges from 27.29 to 46.90 dS/m, and SOC content varies from 0.34% to 1.33% (Sadeghi, 2005; Moslehi et al., 2021). Figure 1 shows the different intensities of dieback of grey mangrove trees in the Khor-e-Azini Wetland (Safyari, 2017).

2.2 Methods

2.2.1 Classification of dieback

In the study area, we assessed the severity of dieback of grey mangrove trees based on multiple factors, including the number of dried trees, the proportion of trees exhibiting dieback symptoms in the field, and the count of contaminated, dead, and healthy trees. If over 50% of the trees displayed signs of illness and dryness, it was classified as severe dieback. If fewer than 50% of the trees were dry and ailing, it was categorized as moderate dieback. Finally, if up to 15% of the trees showed signs of sickness and dryness, it was considered as low dieback (Fig. 1). Notably, areas devoid of dieback served as control groups (Duke et al., 2003). The design employed in this research was completely randomized. After selecting both dried and control groups of each treatment, we randomly established 10 m×10 m plots. Each treatment comprised 10 plots, with four distinct treatments, resulting in 40 plots (Mafi Gholami and Jafari, 2020).

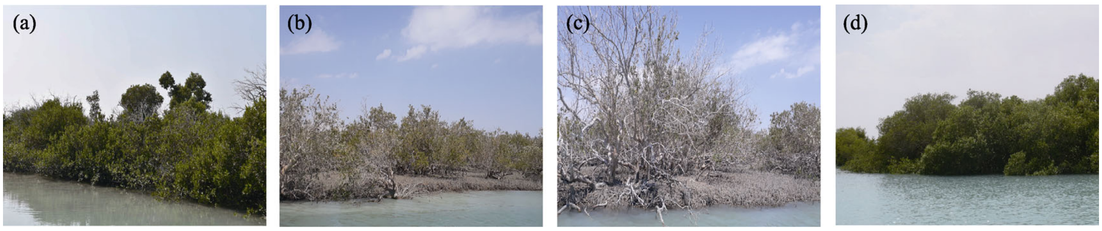

Fig. 1 Different intensities of dieback of grey mangrove trees in the Khor-e-Azini Wetland, Iran. (a), low dieback; (b), medium dieback; (c), severe dieback; (d), control.

2.2.2 Demography of grey mangrove trees

The vegetative characteristics and vitality level of all trees within each plot were measured and documented using the Swiss statistical method (Zubeiri, 2004). Tree vitality was assessed using qualitative characteristics including canopy shape, leaf color, and dry micro-branches. These characteristics were evaluated observationally and graded as good, medium, or poor (Kenshlo, 2004). Other variables under scrutiny included the height of sample trees (Komiyama et al., 2008), determined using a precision measuring tape, and the collar diameter (cm) assessed with a measuring tape (Komiyama et al., 2008). The canopy area was calculated by measuring the two perpendicular diameters of the canopy with a meter and then employing Equation 1 (van Laar and Akca, 2007).

$$\mathrm{CC}=\frac{\pi}{4}\times\overline{\mathrm{CD}}^2, \tag{1}$$

where CC is the canopy area (m^2); and $\overline{\mathrm{CD}}$ is the mean of the two perpendicular diameters of the canopy (m). Notably, the health status of both trees and investigated seedlings within each plot was categorized into three groups: healthy, sick, and dead (Duke et al., 2003). These categories were documented after an observational evaluation (Table 1).

Table 1 Classification and characteristics of grey mangrove trees

Classification	Description
Healthy	Healthy leaves without any symptoms of disease
Sick	Wilted disease, yellow leaves (chlorosis), necrotic spots, leaf burn, canopy cover, and low foliage
Dead	Wholly dried up and dead

2.2.3 Demography of grey mangrove seedlings

Through examining the trees across different plots, we investigated the demography of grey mangrove seedlings in 5×5 quadrats of each plot. Tree density per square meter was recorded (Duke et al., 2003; Yaqubzadeh et al., 2020).

2.2.4 Height, status, and density of pneumatophores

To assess the condition of pneumatophores in each plot, we randomly selected ten aerial roots of grey mangrove trees. Subsequently, we measured the distance from the tip of each aerial root to the sediment surface. To gauge the impact of sediment on dieback, we also measured and recorded the distance between the sediment surface and the cable roots. We identified five trees at the plot's center and four corners to determine the pneumatophore density. Micro-plots measuring 1 m×1 m were established at 1-m intervals from the tree trunk, and the number of aerial roots within these micro-plots was tallied (Cue and Ninomiya, 2007). Then, the count of aerial roots, serving as a valuable indicator to ascertain the number of pneumatophores buried by sediment in each plot, was averaged (n=5). This average was used to determine the density of aerial roots at each distance from the tree within a single plot (Duke et al., 2001; Duke et al., 2003).

2.2.5 Physiological properties

A systematic approach was employed to assess the physiological characteristics of grey mangrove trees within various treatments, specifically those affected by dieback. Ten trees were selected randomly from each plot, and four leaves were collected, one from each cardinal direction. These four leaves were subsequently combined to create a composite sample. Ten such composite leaf samples were assembled for physiological analysis for every plot. This process yielded 40 leaf samples, divided equally between the control and dieback treatments. Without delay, all collected samples were transported to the laboratory and promptly frozen using liquid nitrogen. Subsequently, they were stored in a freezer at –80°C to maintain their integrity. Arnon method (1967) was employed to determine the chlorophyll and carotenoid levels in these samples.

To initiate the analysis, we placed 0.2 g of frozen leaves into a mortar and ground them thoroughly using liquid nitrogen. Then, 20 mL of 80% acetone was added to the sample and filtered the mixture using a vacuum pump. We separated the plant residue from the liquid by centrifuging the solution at 2700 r/min for 10 min at 25°C. The upper extract from the centrifugation process was then carefully transferred to a glass flask, and its volume was measured. A portion of this extract was subsequently poured into the cuvette of a spectrophotometer. The absorbance of the extract was individually read at wavelengths of 645, 663, and 470 nm. The amount of pigment (mg/g fresh weight) was calculated using the following equations (Khlifi et al., 2013).

$$\text{Chlorophyll } a=[12.7(A_{663})–2.69(A_{645})]\times V/W, \tag{2}$$

$$\text{Chlorophyll } b=[22.9(A_{645})–4.68(A_{663})]\times V/W, \tag{3}$$

$$\text{Total chlorophyll}=[20.2(A_{645}) +8.02(A_{663})]\times V/W, \quad (4)$$

$$\text{Carotenoid}=(1000A_{470}-1.8\text{Chl}a-85.02\text{Chl}b)/198, \quad (5)$$

where A_{645}, A_{663}, and A_{470} are the optical absorption at wavelengths of 645, 663, and 470 nm of the samples, respectively; V is the final volume of ethanol consumed (mL); and W is the tissue weight (g).

2.2.6 Water properties

To ascertain the acidity and EC of water in each treatment, we randomly excavated three soil cores measuring 30 cm×30 cm×30 cm within each plot of the stand. After filling the pits with water, we transported water samples to the laboratory to determine acidity and EC (Duke et al., 2003). Measurements were conducted using pH and EC meters (Richard, 1954).

2.2.7 Chemical properties of sediment, roots, and leaves of grey mangrove trees

Five trees were randomly selected within each plot for sediment sampling in each dieback treatment. Subsequently, soil samples were collected beneath the canopy of these trees in the rhizosphere area at a depth of 10 cm. Five sediment samples gathered in each plot were amalgamated, resulting in a composite sediment sample (10 sediment samples for each treatment and totaling 40 sediment samples) (Moslehi et al., 2021). Samples were combined to create a composite sample for each respective organ, consisting of 10 leaf samples and 10 root samples for each dieback treatment (Machado et al., 2002). The combined root and leaf samples were first air-dried and subsequently subjected to complete drying at 75°C for 24 h (Einollahipeer et al., 2013). The collected sediment was also entirely air-dried in the shade. The dried sediment, leaf, and root samples were pulverized using a porcelain mortar and passed through a 63-μm sieve to eliminate impurities and coarser particles. Subsequently, we added 5 mL of concentrated nitric acid (65%) to 0.5 g of dry matter. The prepared mixture was initially digested for 1 h at laboratory temperature and then for 3 h at 90°C on a hot plate. After cooling, the mixture was filtered using Whatman No. 42 filter paper, reaching a final volume of 50 mL with double-distilled water, thereby creating the desired extract for measuring metals. The samples were stored at 4°C. Heavy metals were measured in the samples using an atomic absorption device with a cathode lamp, expressed in mg/L (Dewis and Freitas, 1970). After sieving part of the sediment samples through a 2-mm mesh, 1 g of the resulting material was used to measure organic carbon through the Walky-Black oxidation method (Page et al., 1992). This study assessed three heavy metal elements: nickel, cadmium, and zinc.

2.3 Data analysis

Data analysis was conducted utilizing SPSS v.26.0. The normality of data distribution was assessed through the Kolmogorov-Smirnov test, while the homogeneity of variance was verified using the Levene test. All measured properties, chlorophyll, carotenoids, and leaf metals among different treatments, were analyzed using a one-way analysis of variance (ANOVA). Mean comparisons were performed utilizing Duncan's multiple-range test.

3 Results

3.1 Demographic and vegetative characteristics of trees and seedlings

As shown in Table 2, control trees exhibited the highest percentage of tree density, while density significantly decreased with increasing dieback severity. The number of ailing trees was notably increased under dieback treatments, particularly in cases of severe dieback, suggesting unfavorable conditions under these treatments. Furthermore, the density and health of seedlings within each treatment were also assessed. The results revealed that the highest percentage of seedling density was found under control treatment, with decreases under other treatments, reaching its minimum under severe dieback treatment. As dieback severity increased, the number of healthy seedlings decreased, and their mortality rate concurrently increased (Table 2).

Table 2 Density of grey mangrove trees and seedlings under different dieback treatments

Plant type	Type of dieback	Plant density (%)		
		Healthy	Sick	Dead
Grey mangrove trees	Control	98.80	1.20	0.00
	Low dieback	60.27	39.73	0.00
	Moderate dieback	56.94	43.06	0.00
	Severe dieback	35.71	62.50	1.79
Grey mangrove seedlings	Control	98.40	1.60	0.00
	Low dieback	84.00	16.00	0.00
	Moderate dieback	40.70	33.30	26.00
	Severe dieback	37.50	0.00	62.50

Results indicated a significant divergence in the vitality of grey mangrove trees across various dieback treatments ($P<0.01$). According to these results, the highest vitality was observed under control treatment, with a value of 4.28, demonstrating a substantial disparity compared with severe and moderate dieback treatments, which recorded values of 2.83 and 3.84, respectively (Fig. 2a). ANOVA showed a significant difference in the density of aerial roots among grey mangrove trees at various distances from the tree under different dieback intensities ($P<0.01$). On average, the density of aerial roots under control treatment was the highest, registering a value of 103.62 cm/m^2, significantly greater than that observed under other treatments (Fig. 2b). Notably, following the control treatment, low dieback treatment exhibited the highest aerial root density, being 85.36 cm/m^2. Conversely, the density of aerial roots in moderate and severe dieback treatments fell within the same range, displaying no significant difference (Fig. 2b).

Height of aerial roots under the control treatment (10.84 cm) exceeded those of low, medium, and severe dieback treatments, being 7.87, 7.92, and 7.79 cm, respectively ($P<0.01$; Fig. 2c). Additionally, height of cable roots to the sediment surface was the lowest under severe dieback treatment (7.31 cm) and exhibited a significant difference ($P<0.01$) compared with control (11.39 cm), low dieback (11.20 cm), and medium dieback (11.19 cm) treatments (Fig. 2c)

Height of grey mangrove trees exhibited a significant difference among various treatments ($P<0.05$). Results showed that the height of trees under low dieback treatment was the lowest (Fig. 2d). In contrast, the other treatments, including the control had no significant differences in height, collar diameter, and canopy area (Fig. 2e and f).

3.2 Lead, cadmium, and nickel contents in the sediment, roots, and leaves of grey mangrove trees

Results revealed that the highest lead concentration in the sediment was observed under severe dieback treatment, whereas the lowest lead concentration was found under control.

Specifically, lead concentration in sediment was 27.78 mg/L under severe dieback treatment, and was significantly different from other three treatments ($P<0.05$; Fig. 3a). Similarly, in the roots and leaves of grey mangrove trees, lead concentrations were the highest, being 9.62 and 8.10 mg/L, respectively (Fig. 3b and c). Conversely, control treatment had the lowest lead concentrations in both roots and leaves (7.22 and 5.29 mg /L, respectively).

ANOVA result showed a significant difference in the concentration of cadmium only in the sediment ($P<0.01$). In contrast, no significant difference was observed in the roots and leaves. Specifically, severe dieback treatment had the highest cadmium concentration (0.82 mg/L), followed by moderate dieback (0.71 mg/L), low dieback (0.66 mg/L), and control (0.55 mg/L) treatments (Fig. 4a) in sediment. In the roots, the highest and lowest cadmium concentrations were observed under severe dieback and control treatments, respectively. In contrast, in leaves and roots, no significant differences were observed under different treatments (Fig. 4b and c).

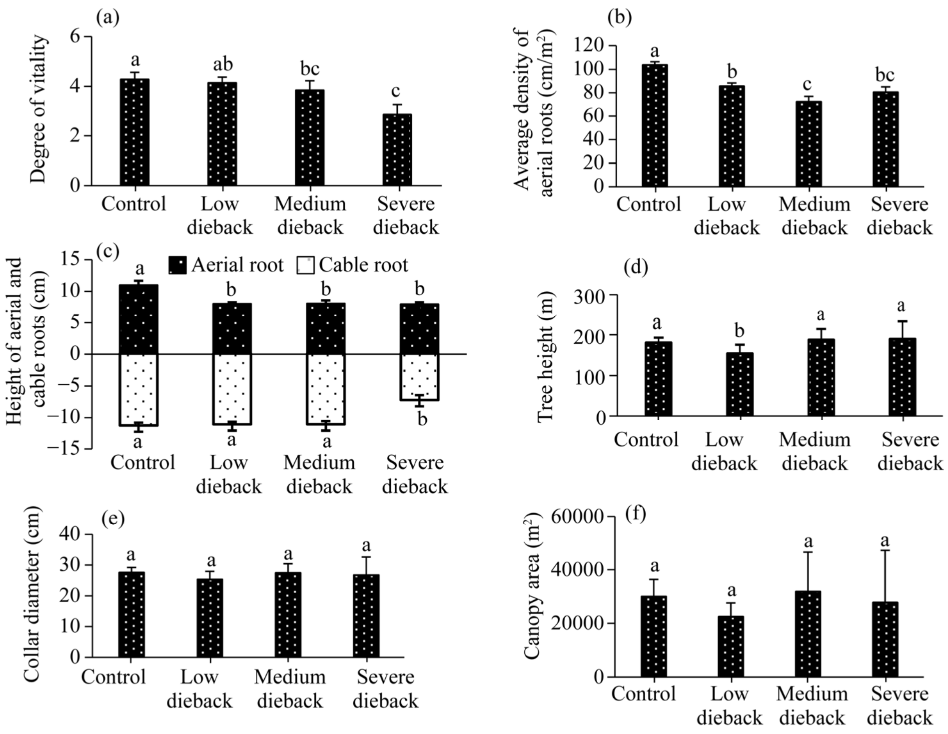

Fig. 2 Degree of vitality (a), density of aerial roots (b), height of aerial and cable roots (c), tree height (d), collar diameter (e), and canopy area (f) under different dieback treatments. Different lowercase letters indicate significant differences among different treatments at $P<0.05$ level. Bars are standard errors.

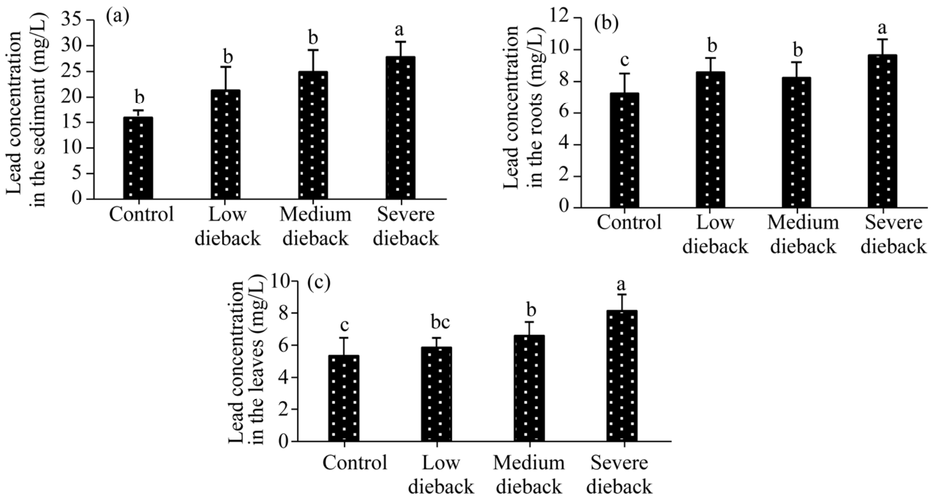

Fig. 3 Lead concentrations in the sediment (a), roots (b) and leaves (c) of grey mangrove trees under different dieback treatments. Different lowercase letters indicate significant differences among different treatments at $P<0.05$ level. Bars are standard errors.

Nickel concentrations in the sediment, roots, and leaves of grey mangrove trees significantly varied under different dieback treatments. The highest nickel concentration occurred in the sediment under severe dieback treatment, being 141.08 mg/L ($P<0.01$; Fig. 5a). In roots, severe and moderate dieback treatments exhibited similar nickel concentrations (39.27 and 37.91 mg/L, with a significant difference ($P<0.01$) from low dieback and control treatments (33.74 and 30.15 mg/L, respectively)) (Fig. 5b). Similarly, severe dieback treatment in the leaves had the highest nickel concentration (1.53 mg/L; $P<0.05$). Notably, low dieback and control treatments exhibited similar nickel concentrations in the leaves and did not significantly differ from each other (Fig. 5c).

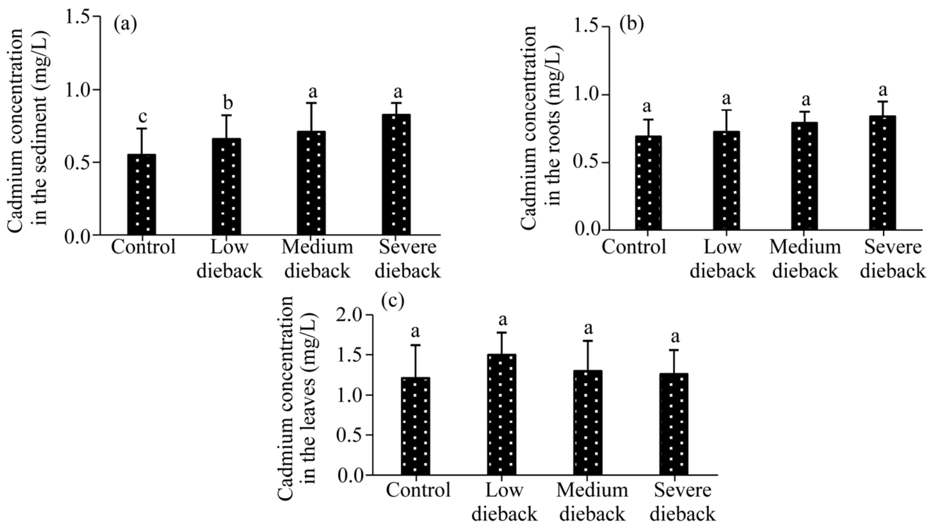

Fig. 4 Cadmium concentrations in the sediment (a), roots (b), and leaves (c) of grey mangrove trees under different dieback treatments. Different lowercase letters indicate significant differences among different treatments at $P<0.05$ level. Bars are standard errors.

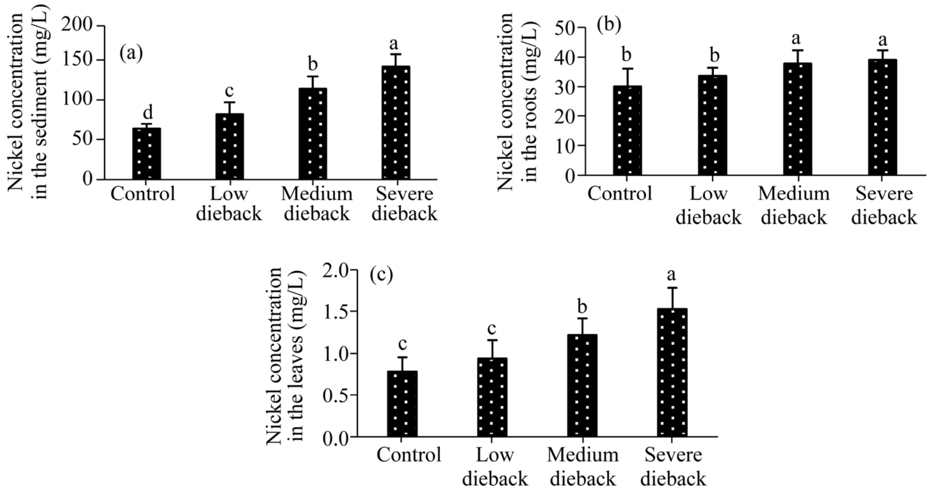

Fig. 5 Nickel concentrations in the sediment (a), roots (b), and leaves (c) of grey mangrove trees under different dieback treatments. Different lowercase letters indicate significant differences among different treatments at $P<0.05$ level. Bars are standard errors.

3.3 Metal distribution in the organs of grey mangrove trees

Significant differences in lead concentration were found between roots and leaves, except low dieback treatment. Lead concentration in the roots was higher than that in the leaves (Fig. 6a). Significant differences in cadmium concentration were observed in both root and leaf organs, except for low dieback treatment. Cadmium concentration in the leaves was higher than that in the roots (Fig. 6b). Nickel concentration was greater in the roots than in the leaves. Notably, nickel concentration was considerably higher than other metals (Fig. 6c).

3.4 Water property and soil organic carbon

Significant differences in water EC were found across various dieback treatments ($P<0.01$). However, no significant differences were observed in acidity among treatments ($P>0.05$). Results indicated the highest value was 22.06 dS/m under severe dieback treatment and the lowest was found under control (Fig. 7a). According to the results, acidity levels under dieback treatments

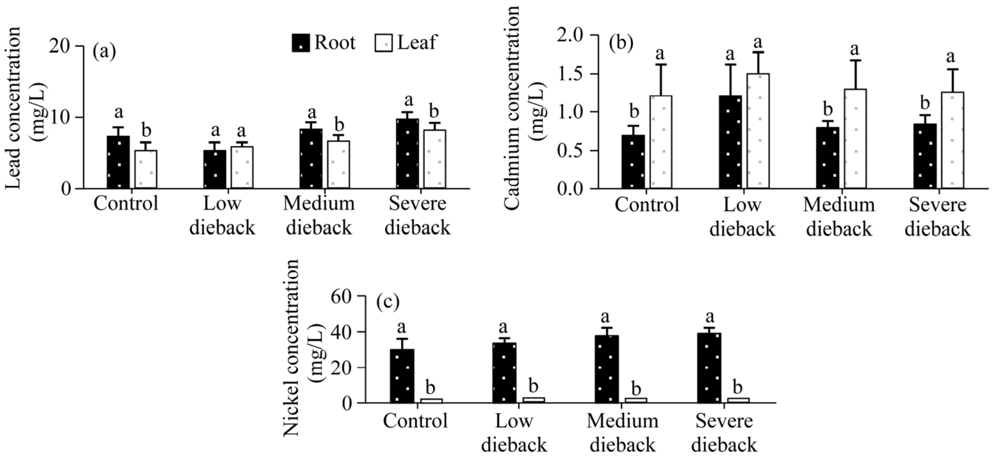

Fig. 6 Metals contents between roots and leaves under different dieback treatments. Different lowercase letters within the same treatment indicate significant differences between roots and leaves at $P<0.05$ level. (a), lead; (b), cadmium; (c), nickel. Bars are standard errors.

were higher than that under control, albeit without statistical significance (Fig. 7b). Result demonstrated a significant difference in SOC among different treatments ($P<0.01$). SOC followed the pattern: severe dieback (0.92%)>medium dieback (0.84%)>low dieback (0.67%)>control (0.64%) with significant differences (Fig. 7c).

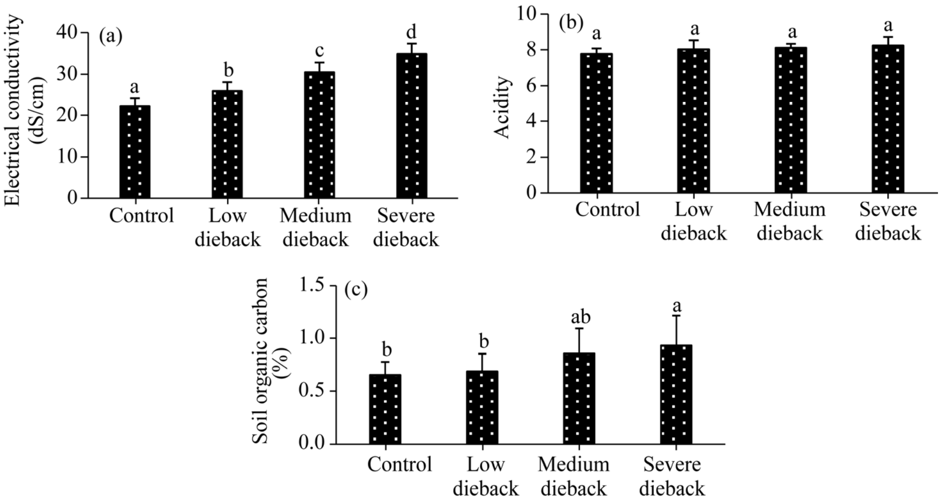

Fig. 7 Electrical conductivity (a), acidity (b) of water, and soil organic carbon (c) under different dieback treatments. Different lowercase letters indicate significant differences among different treatments at $P<0.05$ level. Bars are standard errors.

3.5 Chlorophyll *a*, *b*, total chlorophyll, and carotenoid contents in leaves

Results revealed significant differences in chlorophyll *a*, *b*, and total chlorophyll under different treatments ($P<0.01$), while no significant difference was observed in carotenoid content ($P>0.05$).

Chlorophyll *a*, *b*, and total chlorophyll concentrations were the highest under control treatment and the lowest under severe dieback treatment (Fig. 8). Specifically, chlorophyll *a* and b were 1.89 and 1.03 mg/g, compared with other treatments within the same group (Fig. 8a and b). Additionally, total chlorophyll contents in the control treatment and low dieback treatment, measuring 2.92 and 2.83 mg/g, respectively, were in the same category while showing a significant difference from medium (2.24 mg/g) and severe (1.45 mg/g) dieback treatment (Fig. 8c).

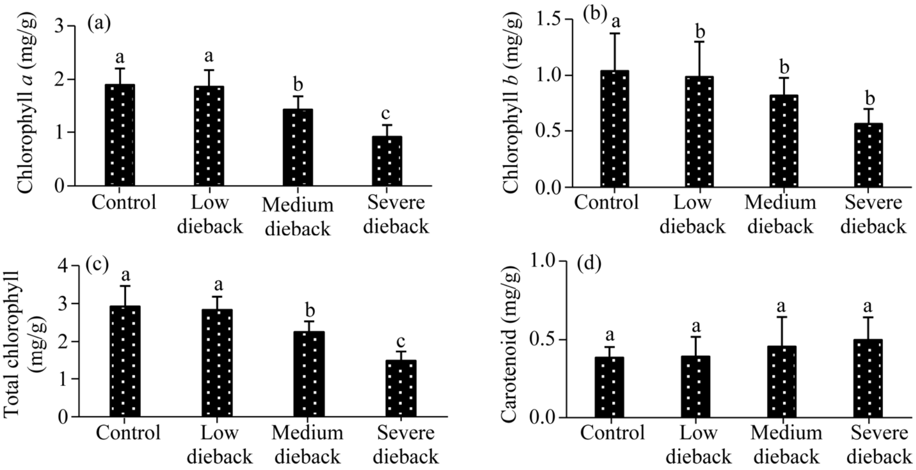

Fig. 8 Chlorophyll *a* (a), chlorophyll *b* (b), total chlorophyll (c), and carotenoid (d) concentrations in grey mangrove trees under different dieback treatments. Different lowercase letters indicate significant differences among different treatments at $P<0.05$ level. Bars are standard errors.

4 Discussion

Mangrove dieback reduces ecosystem functions and services, significantly impacting coastal protection, nutrient cycling, carbon sequestration, and habitat for biodiversity (Lovelock et al., 2017; Sippo et al., 2020; Budiadi et al., 2023). In this study, we examined the demography and vegetative characteristics of grey mangrove trees experiencing different levels of dieback. The research revealed that the control treatment had the highest tree density, vitality, aerial root density, and aerial root height. As dieback intensity increased, these parameters decreased. Numerous studies have shown that dieback affects species composition, density, health, and demography (Duke et al., 2001; Ellison and Zouh, 2012) This phenomenon may be attributed to salinity, heavy metals, pests, diseases, and climate change (Osorio et al., 2017). Furthermore, severe dieback treatment had the lowest height of cable roots near the sediment surface, indicating sediment erosion in areas with severe dieback intensity. Cable roots are consistently exposed to anaerobic conditions as sediment accumulates, leading to the death of mangrove trees (Adams and Human, 2016). The sediment deposition can bury the pneumatophores, suffocating mangrove roots and reducing the health of grey mangrove trees (Nardin et al., 2021).

No significant differences were observed between different dieback treatments regarding tree height. This lack of variation may be attributed to the relatively short duration of our investigation and the fact that these trees have reached maturity. Long-term monitoring is essential for a more comprehensive understanding of these grey mangrove trees. The study on seedlings' demographic and vegetative characteristics of grey mangrove exposed to different dieback intensities revealed that all vegetative characteristics, including seedling density and height, were the highest under control treatment. However, there was a decrease under dieback treatments. Young individuals, such as seedlings, are highly susceptible to various factors contributing to mangrove dieback. Awal (2014) suggested that significant differences in mangrove's regeneration can be observed, and the direct cause may not necessarily be dieback.

In terms of the impact of heavy metals on mangrove forests, numerous studies, including Hoq et al. (2002), Sarkar et al. (2003), Sarika and Chandramohanakumar (2008), Awal et al. (2009), and Awal (2014), have demonstrated their responsibility for dieback in mangrove forests. Heavy metals, such as lead, cadmium, and nickel, are potentially toxic to plants, microbes, aquatic animals, and humans (Dubinski et al., 1986). Our research found varying levels of heavy metals in the grey mangrove trees' sediment, roots, and leaves across different dieback treatments. Specifically, lead concentrations were the highest in the sediment under severe dieback treatment and the lowest under control. Roots and leaves contained the highest lead concentrations under

severe dieback treatment, while control treatment had the lower concentrations. High levels of heavy metals, like lead, can lead to symptoms of metal excess, potentially causing vascular blockages in plants (Yim and Tam, 1999), and ultimately reducing plant growth (MacFarlane and Burchett, 2002). Regarding cadmium, our results indicated a significant difference only in the sediment across different treatments. In contrast, no significant difference was observed in the roots and leaves. Due to higher concentrations of heavy metals, such as cadmium, under severe dieback compared with other treatments and the control, it can be considered as one of the factors contributing to dieback occurrence of grey mangrove trees. Similarly, the highest nickel concentrations in the sediment, roots, and leaves were found under severe dieback treatment. Based on these findings, we implied that heavy metals play important roles in the increased incidence of dieback in grey mangrove trees. Indeed, Awal (2014) reported that the effect of metals on dieback may be more related to the amounts present in plant tissues rather than in the sediment.

In this study, lead concentrations under different dieback treatments (except in low dieback) were higher in the roots than in the leaves. In contrast, cadmium concentrations in the two organs were different. According to environmental quality standards, cadmium thresholds for biota and sediment were 0.001 and 0.700 mg/L, respectively (Dermawan et al., 2019). Our findings indicated the high cadmium toxicity under severe dieback treatment for sediment and there was no significant difference in the roots and leaves (Dermawan et al., 2019). Nickel amount in the two organs under different treatments showed that roots had higher levels than leaves. Internal physiological mechanisms enable mangroves to tolerate heavy metals (Awal, 2014). Our results indicated that the main metals in Iranian mangrove forests were cadmium, nickel, and lead, in which nickel concentrations was notably higher than other metals. Furthermore, acidity under different treatments showed no significant differences. This outcome aligns with the findings of Awal (2014), who suggested that the absence of significant differences between plots for most parameters (except pH) may be due to minor variations over relatively small distances between plots or the selection of specific plots. Analysis of SOC content revealed the highest amount under severe dieback. This result is consistent with that of Duke et al. (2003). Under dieback treatments, carbon stocks increased due to adding dead branches to the soil and reducing CO_2 emissions from anaerobic sediment. Krauss et al. (2018) indicated that sediment desiccation resulting from mangrove forest mortality prevents oxidation of the sediment profile through continuous tidal inundation. However, over longer timescales, a gradual reduction in carbon outflow from dead mangrove forests is expected, as soil carbon stocks will be depleted through oceanic outflow (Sippo et al., 2019).

The analysis of chlorophyll *a*, *b*, and total chlorophyll contents under dieback and control treatments indicates that dieback negatively impacts their concentrations. Furthermore, chlorophyll *a*, *b*, and total chlorophyll concentrations decreased in correlation with dieback intensity. While no significant difference was observed in carotenoid concentrations under various treatments. Carotenoids concentration was higher under severe dieback and other dieback treatments compared with control. Dieback in mangrove forests directly affects photosynthesis due to the reduced area (Agrios, 2005; Aeby and Santavy, 2006). Consequently, this leads to a reduction in the average leaf life span (Reef et al., 2010). Several factors, including disease, grazing, and cutting, contribute to the reduction in photosynthetic tissue, which, in turn, triggers dieback events in grey mangrove trees (Campbell et al., 2014, Lewis III et al., 2016; Rossi et al., 2020). All these factors collectively point to a pollution source in grey mangrove forests. The proximity of these grey mangrove forests to the Sirik Port has created a potential source for pollution, such as heavy metals, which subsequently impacts the survival of these grey mangrove forests. Dittman et al. (2022) also confirmed that the proximity of mangrove forests to pollution sources contributed to their dieback.

5 Conclusions

In this study, the proximity of the study area to the pollution source, Sirik Port, emerges as the

most significant factor driving the dieback of grey mangrove forests within the Khor-e-Azini Province, Iran. The findings revealed that sediment erosion and the presence of heavy metals have escalated to a hazardous level, directly contributing to the dieback of grey mangrove forests. As dieback intensifies, physiological, vegetative, and plant production characteristics experience a marked decline. The plant's reproductive capacity also diminishes, impacting its overall health and vigor. These multifaceted challenges render the grey mangrove forests vulnerable to harsh environmental and human-induced stresses, preventing it from effectively repairing itself. Consequently, these factors cumulatively lead to plant mortality and exacerbate the dieback issue in this area. As a solution, it is strongly recommended to institute comprehensive management plans to rejuvenate severely affected areas by dieback.

Conflict of interest

The authors declare that they have no conflict of interest.

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Author contributions

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